35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

A Novel Edge Tracking Approach for Cornea in Optical Coherence Tomography Anterior Chamber Images*

Wenliang Du, Xiaolin Tian, Yankui Sun

Abstract— **A new edge tracking method for cornea in optical coherence tomography anterior chamber images has been proposed in the paper. The new approach detects the edge of cornea outside the cornea first. Then, it fixes the detected edge, which follows the future knowledge of cornea, to make sure that only the real edge of cornea could be left. Finally, the method fits the fixed edge by fourth order least squares. The advantage of this proposed method is that it could fit the edge of cornea even for abnormal corneas.**

I. Introduction

Optical coherence tomography (OCT) is a non-invasive, non-contact, high speed imaging technique and can reach a much higher imaging resolution. This technique was first presented in 1991 by Huang et al. [1]. It has been widely used to diagnose various retinal and anterior chamber eye diseases [2], [3].

But OCT images suffer from speckle noise, which reduces imaging contrast and makes boundaries difficult to be distinguished from background [1], [4]. As far as we know, there is no fast and simple algorithm, which can reduce almost all speckle noise while protect the edge of region of interest completely for all anterior chamber OCT images. That is the region of interest (ROI) may be changed after denoising, which may bring unexpected result to us (see Fig. 1). And the abnormal cornea could not be filled up easily by image enhancement or any other methods.

Nowadays, many premium edge tracking methods have been proposed [5-7]. But those methods could obtain the exactly edge of cornea for the abnormal cornea hardly.

Indeed, we could not get all the edge of the abnormal cornea. However, if we can just obtain the real edge then fitting it, then we can get the edge curve no matter how abnormal the cornea is. Therefore, this paper proposes a novel edge tracking approach for the abnormal cornea. Firstly, this approach gets the positions of anterior chamber angle points (ACAPs) and the temporary central corneal thickness (TCCT) by [8]. Secondly, the approach tracks the edge outside the cornea and ends at the ACAPs. Then, it fixes the detected edge following the future knowledge of cornea. At last, the approach fits the fixed edge by fourth order of least squares. Experimental results have shown that this proposed approach obtains the edge of abnormal cornea effectively.

Fig. 1 Denoised anterior chamber OCT images with abnormal cornea

II. The New Proposed Edge Tracking Approach

The new approach is proposed for the abnormal cornea, that this section meanly describes tracking, fixing and fitting, which focus on lower corneal edge. And this section starts by defining the notation that will be used throughout the paper, followed by a detailed description of the approach depicted in the block diagram (see Fig. 2). We can see that the approach processes tracking and fixing separated as left edge tracking, right edge tracking and left edge fixing and right edge fixing. The left edge and right edge are divided by central column of the image. But the left edge and the right edge are processed as the same method. Therefore, this section uses the left lower corneal edge as the sample for description.

A. Notations

The definitions of the variables used in this paper are listed here:

1) Original grayscale image: $I(i,j)$, $(i,j)\in[1,M]\times[1,N]$, M and N are the width and length of the image respectively. $I_{denoised}$ is the denoised image of $I(i,j)$.
2) S_{edge} and S_{out_edge} are the set of edge obtain by Edge Tracking and Edge Fixing respectively.
3) D_{ACAPs} is the distance between ACAPs.
4) P_{apl}, P_{apr} and P_{mid} are the positions of left angle point, right angle point and crossover point of central column across line linking ACAPs, respectively.
5) L_{fix} is the reference length used in Edge Fixing.
6) Point Q is the reference point along with the line linking ACAPs. Point O is the reference point for algorithm 2 in this paper below.

*Resrach supported by the Science and Technology Development Fund of Macao (No. 063/2010/A), and the National Natural Science Foundation of China (No.60971006).

Wenliang Du is with the Faculty of Information Technology, Macau University of Science and Technology, Macao SAR, China (phone: +853-63589041; e-mail: du_wenliang@qq.com).
Xiaolin Tian is with the Faculty of Information Technology, Macau University of Science and Technology, Macao SAR, China (e-mail: xltian@must.edu.mo).
Yankui Sun is with Department of Computer Science and Technology, Tsinghua University, Beijing, China (e-mail: syk@mail.tsinghua.edu.cn).

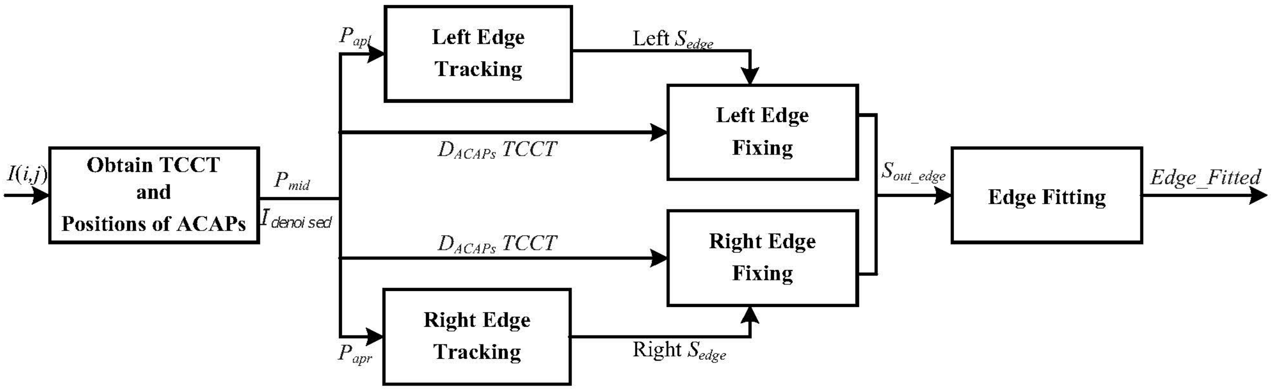

Fig. 2 The new edge tracking approach for cornea

Algorithm 1 Edge Tracking

Point Q travels from P_{mid} to ACAPs while detects the pixel above Q whose value is bigger than 0 first. $j(Q)$ stands for the Q's column currently. i is the row from $i(Q)$ to 1 where $i(Q)$ is the Q's row currently. We suppose that S_{edge} already got its first correct edge stored in $S_{edge}(i(P_{mid}),j(P_{mid}))$. As the future knowledge, the edge we got must be monotone decreasing. So we use i_{high} to help us keep the rule above.

$i_{\text{high}}=S_{edge}(i(P_{mid}))$
if $I_{denoised}(i,j(Q))>0$
  if $I_{denoised}(i\text{-}1,j(Q))>0$ **&** $I_{denoised}(i,j(Q)\text{-}1)>0$ **&** $i<=i_{\text{high}}$
    $S_{edge}(i,j(Q))=(i,j(Q))$
    $i_{\text{high}}=i$
  end if
end if

Let the S_{edge} we have gotten be a set which has no zero.

B. Obtain TCCT and Positions of ACAPs

The algorithm proposed by [8] uses threshold segmentation and median filtering gets the denoised image $I_{denoised}$ like Fig. 1 firstly. Then, it calculates the TCCT in the central column of $I_{denoised}$. Next, the algorithm obtains P_{apl}, P_{apr} and P_{mid} by biggest connected region's method. Finally, it calculates the distance between ACAPs as D_{ACAPs}. P_{apl} and P_{apr} are used as the finishing points of Edge Tracking. P_{mid} is the starting point of Edge Tracking. TCCT and D_{ACAPs} are used to calculate L_{fix} in Edge Fixing.

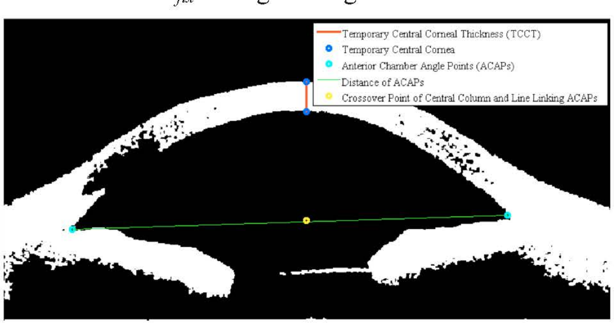

Fig. 3 Obtain TCCT, position of ACAPs and P_{mid} by [8]

C. Edge Tracking

We suppose that the positions of ACAPs have been gotten correctly, that there are no ROI's points along with the line linking ACAPs. Therefore, this new approach proposes a referenced point, which is called as Point Q. This point travels from P_{mid} to ACAPs while detecting the edge above it follows the future knowledge of cornea as S_{edge} (see Algorithm 1).

Fig. 4 Set of left edge got by Edge Tracking

D. Edge Fixing

In this procedure, we extract some key parameters which can help us to reduce the fake edge (see in Fig. 4) obtained by Edge Tracking. And, the flow chart of Edge Fixing is shown as Fig. 5.

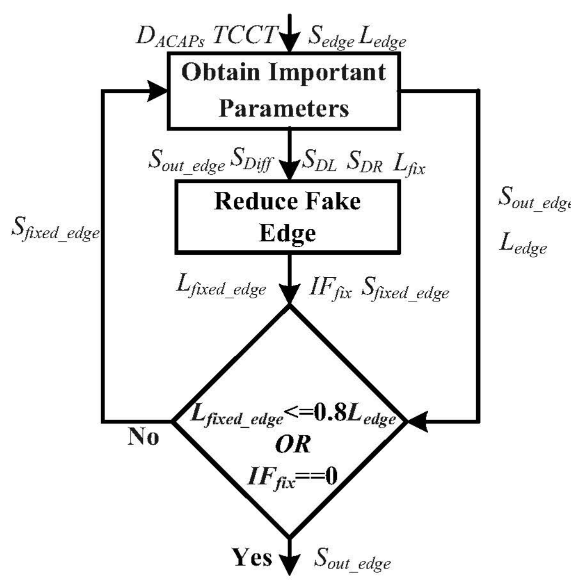

Fig. 5 Flow chart of Edge Fixing

Where L_{edge} and L_{fixed_edge} are the length of S_{edge} and S_{fixed_edge} respectively; S_{Diff}, S_{DL} and S_{DR} are the set of *Diff*, *DL* and *DR*. *Diff*, *DL* and *DR* are the parameters for helping fix S_{edge}. IF_{fix} records whether S_{out_edge} was fixed, if S_{out_edge} was fixed IF_{fix} equal to 1, otherwise IF_{fix} equal to 0.

As we can see in Fig. 5, Edge Fixing can be divided into three steps: Obtain important parameters, Reduce fake edge and Decision. Details of the steps will be described below.

1) Obtain Important Parameters: this step traverses the input of edge from top to end for obtaining S_{Diff}, S_{DL} and S_{DR}. Fig. 6 illustrates one station of the traversal. Where A is the point we traversing. C is the first point which is higher than A and its horizontal distance with A is longer than L_{fix}. B is the first point which is lower than A and its horizontal distance with A is longer than L_{fix}. L_{fix} is calculated as the following formula:

$$L_{fix}=D_{ACAPs}/(2\times \mathrm{TCCT}) \quad (1)$$

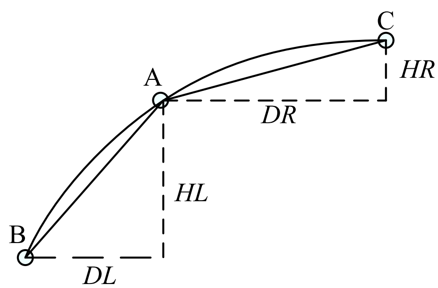

Fig. 6 One station of the traversal in Obtain Important Parameters

HR and *HL* are the vertical distance of points C, A and points A, B. Another important parameter *Diff* is the difference between the slope of points A, B and the slope of points C, A.

$$Diff=HL/DL-HR/DR \quad (2)$$

S_{out_edge} and the input of edge are equal to S_{edge} in the first cycle of the Edge Tracking, and they are equal to S_{fixed_edge} in the remaining cycles.

We don't calculate the important parameters in the pieces at the top and end of the input of edge (the horizontal length of piece is equal to L_{fix}). Which means that, we won't let those pieces of edge be reduced. Thus, we suppose those edge are obtained correctly, and we need them to fitting the edge especially the end's pieces of edge.

2) Reduce Fake Edge: We can illustrate the fake edge obtained in section *C* as Fig. 7. Where the $P_{\max}$ and $P_{\min}$ are the points which get the maximum and minimum value of S_{Diff}. We can treat $P_{\max}$ and $P_{\min}$ as the point A in Fig. 6, then we can get $P_{\max}B$ and $P_{\min}B$ as point B in Fig. 6 and $P_{\min}C$ as point C.

Generally, we can get $P_{\max}$ and $P_{\min}$ perfectly like they are in Fig. 7. But there are still some particular cases that we could not obtain the ideal $P_{\max}$ and $P_{\min}$. Therefore, we figure out a strict algorithm to reduce fake edge as much as possible (see in Algorithm 2). The algorithm needs to obtain the point P_{ref}. P_{ref} is the point higher than $P_{\min}$ and its horizontal distance with $P_{\min}$ is D_{ref}. D_{ref} is equal to the horizontal distance between $P_{\max}$ and $P_{\min}$.

If the algorithm distinguishes the input of edge need fix, it reduces the edge between $P_{\max}B$ and $P_{\min}C$ and set IF_{fix} to 1. Otherwise, it set IF_{fix} to 0.

Algorithm 2 Reduce Fake Edge

Set a Point *O*, let *O* traverse from $P_{\max}$ to $P_{\min}B$. While calculate the slope of $P_{\min}B$ and *O* and record the set of slopes in S_{ref_slope}. Define L_{ref_slope} as the length of S_{ref_slope} and SL_{ref} as the slope of P_{ref} and $P_{\min}B$.

```
Num_Ref=0
IF_fix=0
S_fixed_edge=S_out_edge
for k=1 to L_ref_slope
    if S_ref_slope(k)>=SL_ref
        Num_Ref=Num_Ref+1
    end if
end for

if Num_Ref>=floor(L_ref_slope/2)
  IF_fix=1
end if

if IF_fix==1
  S_fixed_edge(P_maxB:P_minC)=0
end if
```

Let the S_{fixed_edge} we have gotten be a set which has no zero. Calculate the length of S_{fixed_edge} as L_{fixed_edge}.

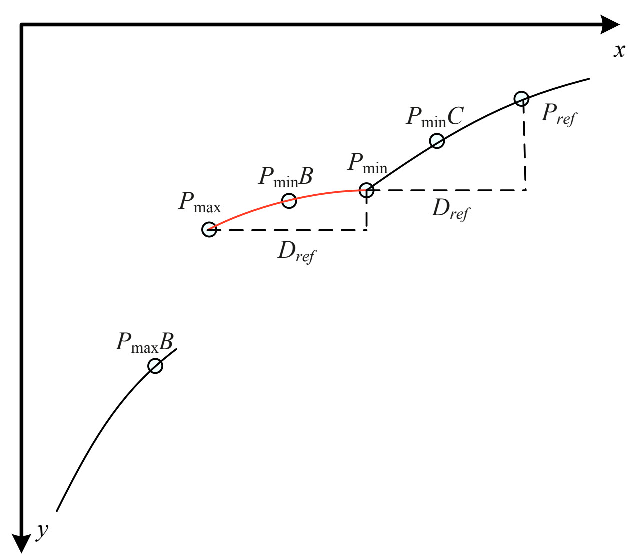

Fig. 7 Diagrammatic sketch for Algorithm 2 (red line is the fake edge we want to reduce)

3) Decision: As illustrated in Fig. 5, if IF_{fix} equal to 0, or the L_{fixed_edge} is less than or equal to eighty percent of L_{edge}, the algorithm output the S_{out_edge} to Edge Fitting. Otherwise, the algorithm output the S_{fixed_edge} to Obtain Important Parameters.

E. Edge Fitting

This method uses fourth order of least squares to fit the S_{out_edge} which is obtained by Left Edge Fixing and Right Edge Fixing.

III. Experimental Results

The depiction of the new proposed meanly focus on the lower corneal edge. For upper corneal edge, we can track it easily even don't need to fix it. We have used 26 anterior chamber OCT images to be our training samples. Moreover, the novel approach was tested with 54 other anterior chamber OCT images. All the edges of training and testing images can be fitted very well. One sample of Edge Fitting result of Fig. 1 and original image of Fig. 1 has been shown as below:

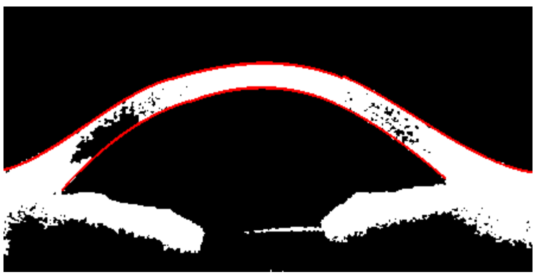

Fig. 8 Result of Edge Fitting of Fig. 1

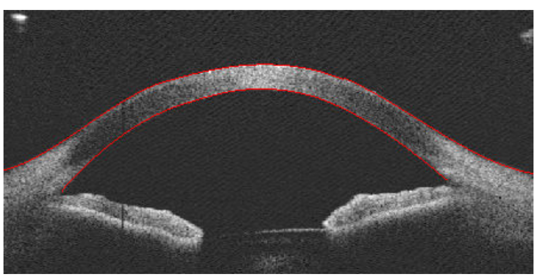

Fig. 9 Result of Edge Fitting of the original image of Fig. 1

Through the results we can see that, the proposed new approach could fit the edge of cornea effectively.

IV. Conclusion

This paper proposes a new edge tracking approach for obtaining the corneal edge even the some parts of cornea is missed after denoising. This method firstly gains $I_{denoised}$, P_{apl}, P_{apr}, P_{mid}, D_{ACAPs}, TCCT, and imports them to Left and Right Edge Tracking. Then, the approach tracks the edge of cornea by using Point Q. For reduce fake edge obtained by Edge Tracking, this approach fixes the edge in Edge Fixing and exports S_{out_edge} to Edge Fitting. Finally, the new approach fits the S_{out_edge} by using fourth order of least squares. The results show that, the new edge tracking approach could fit edge of cornea efficaciously.

Acknowledgment

Many thanks to Shenzhen Moptim Imaging Technique Co. Ltd. for providing the anterior chamber OCT image data.

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